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Loads for the design of the industrial building frame

T.V. Zolina, P.N. Sadchikov*

Astrakhan State Architectural and Construction University, Astrakhan, Russia

** E-mail: pn_sadchikov@mail.ru*

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Abstract. The article considers the issues of assessing the reliability of structures of an industrial building equipped with bridge cranes. The implementation of the research concept is based on a probabilistic approach as the most appropriate to the random nature of technogenic and extreme impacts. A mathematical model is constructed that takes into account the random nature of the formation and perception of the framework structure of the totality of loads. To substantiate the method, an extensive amount of statistical data was generated on the loads of bridge cranes of various types and meteorological information on wind and snow for individual climatic regions of Russia. The stationary probabilistic models for crane and quasistationary models for snow and wind loads are substantiated. The proposed algorithms for their implementation are adapted for the automation of calculations using the software developed by the authors of the article “DINCIB-new”. Numerical calculations of the operability of the frame structures of the operated buildings of production shops under the action of a combination of loads. A comparative analysis of the obtained results with the normative allowed us to conclude that it is necessary to include when forming combinations of loads that affect the change in the stress-strain state of the frame structures of an industrial building, lateral forces. As a result of experimental and theoretical studies, refinements were made to the previously proposed calculation schemes and calculation methods, allowing to design the supporting structures of the frames in accordance with the actual conditions of their actual work.

1. Introduction

One of the main tasks in the design of industrial buildings and structures is to ensure their durability, reliability and stability against both external influences and the impacts that directly arise during their operation [1–8]. The purpose of this study is to clarify the design schemes and methods for calculating an industrial building for crane and atmospheric loads under the real conditions of the actual operation of the frame structures, taking into account the random nature of their manifestation.

During the study of changes in the stress-strain state of an industrial building equipped with bridge cranes, it is necessary to consider internal technological factors that have a significant impact on the performance and safe operation of framework structures. Impacts caused by these factors may be static and dynamic. Their weight in the magnitude of the generalized load is significant and depends on a large number of conditions and parameters of operation of bridge cranes when transferring vertical and horizontal loads on the structures of an industrial facility [9]. In [7], a method was proposed for solving a dynamic problem from the influence of a harmonic load on structures, based on the static accounting of higher vibration modes.

The calculation of industrial buildings for various types of impact correlates with their pronounced random properties. Among the main parameters of the presented perturbations, the following should be highlighted:

– the maximum amplitude of oscillations;
– spectral composition;
– the focus of action;
– duration of the intensive phase.

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When designing and operating such facilities, it is possible to provide the required security with a certain degree of probability. As correctly noted in the article [10], the development of probabilistic methods for calculating building structures follows the path of accumulating factual material on the statistical properties of impacts, while nothing new appears in the formulation of the goals of probabilistic calculation and methods for its implementation. And that's why, when implementing the research concept of authors' article, preference is given to methods for calculating the maximum permissible risk using probabilistic models and reliability theory methods.

For the possibility of constructing a probabilistic calculation of structures with joint application of loads, a promising model for correlating a sequence of random loads [11] based on the generalized covariance method [12, 13]. For the numerical implementation of the calculation algorithm, it is necessary to construct generalized probabilistic models of crane, snow, and wind loads that actually act on the frame of an industrial building. The results of modeling the aerodynamic parameters of structures obtained in [8] were taken into account in the course of this study, since they allow excluding unreasonable reserves of wind load.

To achieve the goal set for the study, the following tasks are required:

1. to identify beyond design basis impacts on the frame of an industrial building arising from the operation of bridge cranes, and their weight in the amount of the generalized load;

2. to clarify the design schemes and methods for calculating the components of the crane load and the components of the atmospheric effects in a probabilistic setting, as the most appropriate for the random nature of their manifestation;

3. adapt the calculation algorithms of an industrial building to the effect of snow and wind loads for software implementation using computer tools.

2. Methods

It is extremely rare that individual elements and the frame of a building as a whole are affected by only one load. In most cases, when calculating, you must immediately take into account several components $\tilde{Q}_i$ [10], the combination of which in accordance with the objectives of the study is considered as the sum of stationary and quasistationary random processes:

$$\tilde{Q} = \sum_{i=1}^{n} c_i \tilde{Q}_i \ , \tag{1}$$

where c_i is the proportion of the i load when converting to the component of the design effort.

Numerical characteristics of the generalized load, presented in the form of a mathematical expectation and a standard, can be defined as:

$$\bar{Q} = \sum_{i=1}^{n} c_i \bar{Q}_i \ , \ s_Q = \sqrt{\sum_{i=1}^{n} \left(c_i \bar{Q}_i Var\left(Q_i\right) \right)^2} \ , \tag{2}$$

where $Var\left(Q_i\right)$ is the coefficient of variation of a random variable Q_i.

Its effective frequency in the absence of a correlation dependence between the individual components of the aggregate, according to the conclusions of V.V. Bolotin [14], expressed as:

$$\omega_Q = \sqrt{\frac{\sum_{i=1}^{n} \left(\omega_i c_i \bar{Q}_i Var\left(Q_i\right) \right)^2}{\sum_{i=1}^{n} \left(c_i \bar{Q}_i Var\left(Q_i\right) \right)^2}} \ . \tag{3}$$

Industrial building under the action of a combination of a large number of loads involved in the oscillatory process. Each of the components of the load factor makes its more or less significant contribution to the joint work of a set of interrelated structures that determine the physical model of the object of study [15–23].

The components of the dynamic load vector vary at different points in time. As one of the options in the automation of calculations, the entire possible range of values may arise from the generation of random numbers according to the normal distribution law with a known expectation $\bar{X}$ and standard s. Because of this approach to determining the range of variation, the random value of the crane load X most fully described by a probabilistic model of a normal stationary random process. In this case, the normalized load deviation γ can be defined as:

$$\gamma = \frac{\left(X - \overline{X}\right)}{s}, \tag{4}$$

and the corresponding emission frequency of random crane load values:

$$\nu_{+}\left(\gamma\right) = \frac{\omega\, e^{-\frac{\gamma^2}{2}}}{2\pi}, \tag{5}$$

where ω is the effective frequency of stationary random process.

The probability of exceeding the normalized level of crane load over time t:

$$Q\left(\gamma, t\right) \cong \nu_{+}\left(\gamma\right)\, t = \frac{\omega\, t\, e^{-\frac{\gamma^2}{2}}}{2\pi}. \tag{6}$$

In addition to crane loads, both at the design and construction stages and at the stage of their operation, a quantitative risk assessment of buildings and structures can be given only when carrying out probabilistic calculations, especially when it comes to extreme impacts on the structures of buildings. When conducting research, the calculated values of crane loads are considered by the authors in the form of random parameters, while assumptions are made about the stochastic representation of their potential deviations determined based on numerous field tests [24, 25].

Except for the considered crane load industrial building is experiencing a number of influences, wearing the natural character of education. These include snow load and wind pressure on the lateral surface of the object.

The value of the snow load has a random nature of changes over time both during a single winter and during long-term seasonal fluctuations of climatic conditions. Consequently, the most acceptable form of its mapping is a probabilistic model of a random process, the parameters of which vary depending on the territorial affiliation of a specific snow region.

According to the results of numerous studies [26] to all known models formalizing a probabilistic approach to the formation of snow load, the most preferred revealed. It consists of presenting a selective sequence of annual highs $\left(S_{m\,i}\right)$ in the form of a continuous random variable distributed according to the Gumbel law. Its probability density is defined as:

$$f\left(S_m\right) = \frac{1}{\beta}\exp\left[\frac{\alpha - S_m}{\beta} - \exp\left(\frac{\alpha - S_m}{\beta}\right)\right], \tag{7}$$

and the corresponding distribution function:

$$F\left(S_m\right) = \exp\left[-\exp\left(\frac{\alpha - S_m}{\beta}\right)\right]. \tag{8}$$

In the study of the wind load, the preferred form of representation of a turbulent flow is the decomposition of its velocity into two components:

$$\upsilon = \overline{\upsilon} + \upsilon' \tag{9}$$

where $\overline{\upsilon}$ is the average wind speed, υ' is the flow rate pulsations.

Any obstacle in the path of the turbulent flow is affected by the corresponding wind load. It refers to the number of short-term loads that do not have a low regulatory value. To assess the forces caused by wind on the object of study, the corresponding load, as in the case of the velocity of the turbulent flow, is decomposed into the sum of two components: the average and the pulsating.

To find the average wind load at a height z above the surface of the earth it is regulated to use the formula

$$w_M = w_0\ k\ C, \quad (10)$$

where w_0 is the standard wind pressure at 10 m above the ground; k is the coefficient to estimate the change in wind pressure in height; C is the aerodynamic coefficient.

The value w_0 determined in accordance with the map of territorial zoning, which shows the distribution of zones of calculated values of wind pressure when choosing the averaging interval $\Delta t = 10\ \min$, exceeded on average once every 50 years. This map is the result of the implementation of a probabilistic model presented in the form of a nonstationary random velocity field of wind flow at a height z_0 above ground. It displays the territorial variability of the parameter under study, the mathematical expectation of the values of which is the result of smoothing the data of long-term observations of meteorological stations, and the standard – the result of processing deviations during such smoothing.

The currently existing methods [2, 10, 27] and the software and settlement systems developed on their basis do not consider all possible components of external influences. They do not always allow one to take into account the spatial work of the structures of buildings and structures, as well as the calculations under the simultaneous action of a whole set of components of the generalized load in a probabilistic formulation.

3. Results and Discussion

The results of experimental studies of vertical crane loads in existing production workshops, processed in the technique of random variables and random processes, revealed their probabilistic features [28]. These should include:

1. stationary random crane load, which is manifested in rapid stabilization and further immutability distributions ordinate and the numerical characteristics;

2. consistency of emission frequencies and frequency characteristics of random processes;

3. the insignificance of deviations of the crane load ordinate (solid line), considered as a continuous random variable X, from the Gauss curve (dashed line), which displays a graph of the probability density function according to the normal distribution law (Fig. 1);

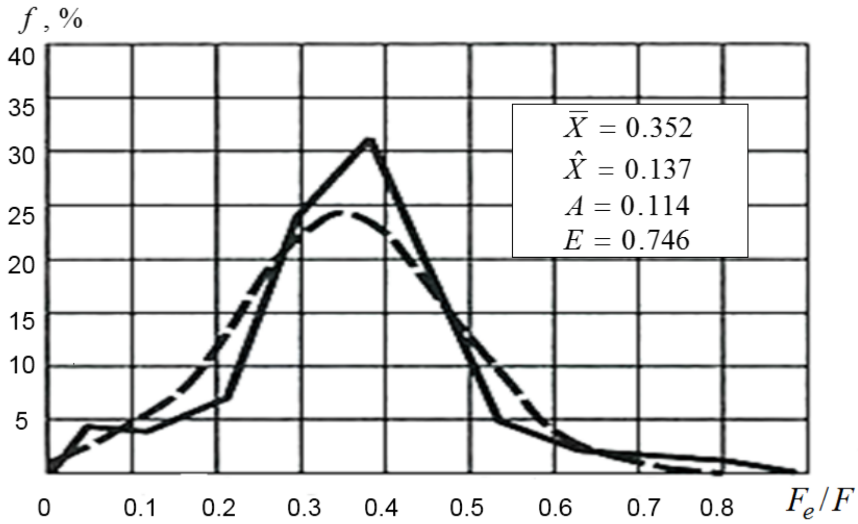


Figure 1. Example of distribution of vertical crane load.

Designations: $\bar{X}$ is the average value, $\hat{X}$ is the coefficient of variation, A is the asymmetry index, E is the excess.

4. high-frequency mixing of random crane load and the absence of a periodic component;

5. allocation of the extreme tail parts corresponding to operations with loads close to the carrying capacity in the distribution of loads caused by the operation of bridge cranes with a flexible suspension.

The analysis of statistical data also indicates the random nature of the dynamics of changes in the magnitude of horizontal loads during the movement of bridge cranes for various purposes [28]. As in the case of vertical loads, these distributions are characterized by the properties of stationarity, elongation of tail parts and normality of statistical representations (Fig. 2).

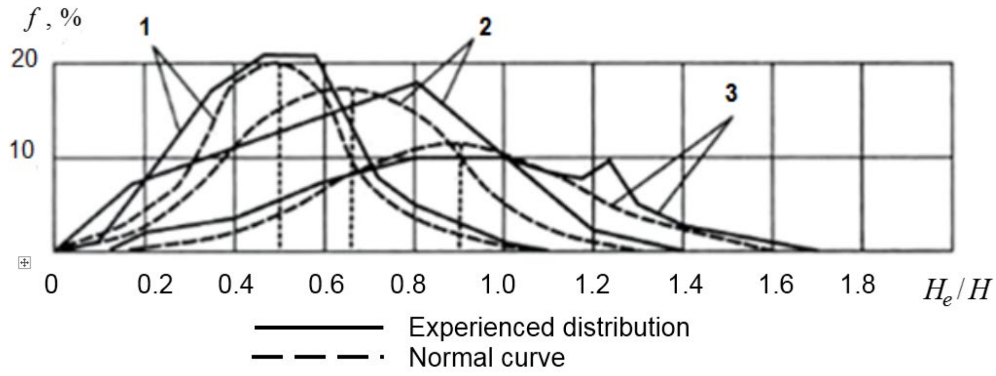


Figure 2. Examples of horizontal crane load distributions:
1 – for cranes with flexible load suspension in areas with a normal gauge;
2 – for cranes with flexible suspension with narrowing and widening of ways;
3 – for cranes with a rigid load suspension.

When analyzing the statistical data obtained during surveys, on the joint distribution of vertical and horizontal crane loads, the following was revealed:

- for sections of tracks with a normal gauge, there is a correlation between the components of the crane load;
- for sections with narrowing and widening of paths, a similar correlation dependence is absent.

It is revealed that between the values of the mathematical expectations of the vertical $\bar{F}$ and horizontal $\bar{H}$ components of the crane load are linear [28]. The equation of this dependence can be represented as: $\bar{H} = k\bar{F}$, in which k is the coefficient of proportionality.

The values of the proportionality coefficients for the main groups of bridge cranes according to the results of processing a large amount of statistical data obtained from surveys of industrial buildings are determined in intervals:

- $k = 0.133 \ldots 0.167$ for a crane with a hard suspension;
- $k = 0.050 \ldots 0.061$ for a multi-wheel crane with a flexible suspension (the number of wheels is 8 or more);
- $k = 0.16 \ldots 0.46$ for the four-wheel crane with flexible suspension.

Expected value $\bar{X}$ and standard s random vertical crane loads were obtained by summarizing the results of the experiments performed with a security of 0.99:

- – for cranes with a rigid suspension, a dependence is revealed

$$\bar{X} = \left(0.66 - 0.243\frac{Q}{Q_{cr} + Q_{tr}}\right)F_0^s;\ s = 0.131F_0^s, \quad (11)$$

where F_0^s is the standard vertical pressure on the crane wheel; Q is the crane capacity; Q_{cr}, Q_{tr} are the weight of the crane bridge and crane truck, respectively;

- for cranes with flexible hanger

$$\bar{X} = 0.758F_0^s;\ s = 0.274F_0^s. \quad (12)$$

These characteristics with the effective frequency ω, completely describe the random vertical crane load and allow solving the problems of probabilistic calculation and evaluation of the reliability of structures under these influences.

So, for example, for a two-span, equal-height building of the ship's hull workshop of the Astrakhan Marine Plant, equipped with bridge cranes with a lifting capacity of 50 tons each with flexible suspensions, the results on the action of vertical crane loads are obtained. Fig. 3 shows the values of bending moments that occur at the vertical pressure of two cranes in probabilistic (solid line) and normative (dashed line) calculations.

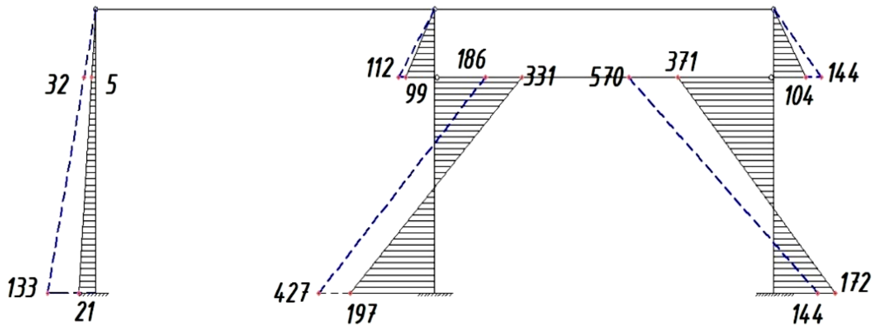


Figure 3. Diagram of bending moments from the vertical pressure of the crane (kN m).

Based on the analysis of experimental data, generalized numerical characteristics of the probability distributions of horizontal loads of the main groups of bridge cranes also were obtained – expectation values $\overline{X}$ and coefficient of variation $Var\left(X\right)$.

In the case of loads caused by the braking of the crane truck, the parameters were calculated using the formulas:

$$\overline{X} = \frac{T_{\text{cr}}^{\text{s}}}{1 - 1.64\ Var(X)},\ T_{\text{cr}}^{\text{s}} = 0.05\frac{Q \cdot 9.81 + Q_{tr}}{n_0},\ Var\left(X\right) = 0.1, \tag{13}$$

where T_{cr}^{s} is the standard value of the brake load on the wheel; n_0 are number of wheels on one side of the crane.

In the course of calculations, there is also the question of the magnitude and direction of the load in the case of simultaneous braking of crane trucks at once by several contiguous cranes. Depending on the time of the beginning and end of the braking of each of them, several options are possible for the change over time of their total impact on the frame of an industrial building [9]. Therefore, the authors of the article consider it necessary to carry out calculations for all known options and to organize the search for the highest values of bending moments, based on which to carry out the design.

The proposed approach allows you to reliably design the load-bearing structures of an industrial building in accordance with the actual conditions of their work during the perception of loads caused by the braking of crane trucks.

The results of numerous theoretical and experimental studies conducted by the authors [9, 24, 28] prove that the physical nature of horizontal impacts from bridge cranes on the frame structure of an industrial building is associated not only with the braking of the crane truck but also with their movement. The kinetics of such a movement causes the appearance of lateral frictional sliding forces. These forces result from the mismatch of the plane of rotation of the crane wheel with the direction of its movement. Theoretically, the movement of a bridge crane on the traveling wheels, installed in the direction of an ideal rail track, is considered as straightforward. However, if such a movement is possible, then it is unstable. With a slight deviation from the listed conditions, the equality between the pulling forces of the drive wheels and the resistance forces of the respective sides of the crane is violated. Failure to comply with this equality indicates the presence of skew forces and transverse reactions of the track, acting on the driving wheels, which leads:

- to the appearance of rotational and transverse movements of the crane within the gaps between the flanges and the heads of the rails;
- to additional loading of metal structures of the crane, traveling wheels and crane rail track.

With regard to accounting and determining the magnitude of lateral forces arising from the movement of the crane with a bias, there is no consensus. Moreover, their values calculated by the formulas proposed by various authors [9] differ several times.

An analysis of the results showed that the values of the lateral forces exceed the braking forces acting on the transverse frames in the plane of which the bridge crane works, and the numerical characteristics of the corresponding random variables are determined:

- for cranes with a hard suspension

$$\overline{X} = 0.1F_{mid}\sum Y; \qquad Var\left(X\right) = 0.5 \tag{14}$$

where F_{mid} is the vertical wheel pressure without load with a cart located in the middle of the bridge; $\sum Y$ is the sum of the ordinates of the influence line when accounting for one crane;

– for multi-wheel cranes with flexible suspension (the number of wheels is 8 and more)

- on track sections with normal gauge

$$\bar{X} = 0.08F_{mid}\sum Y; \qquad Var(X) = 0.45; \tag{15}$$

- in areas with narrowing and extending paths exceeding 40 mm

$$\bar{X} = 0.12F_{mid}\sum Y; \qquad Var(X) = 0.36; \tag{16}$$

– for four-wheel cranes with flexible suspension

$$\begin{aligned} &\bar{X} = 0.1\bar{F}_{\max} + \frac{\alpha\left(\bar{F}_{\max} - \bar{F}_{\min}\right)L_{cr}}{K}; \\ &\bar{F}_{\max} = \left[\frac{Q_{cr}}{2} + \frac{\left(\bar{Q} + Q_{tr}\right)\left(L_{cr} - a\right)}{L_{cr}}\right]\frac{1}{n_0}; \\ &\bar{F}_{\min} = \left[\frac{Q_{cr}}{2} + \frac{\left(\bar{Q} + Q_{tr}\right)a}{L_{cr}}\right]\frac{1}{n_0}; \\ &\bar{Q} = 0.5Q, \end{aligned} \tag{17}$$

$\bar{F}_{\max}, \bar{F}_{\min}$ are the mathematical expectations of vertical pressure on the wheel, respectively, on the most and least loaded side of the crane; α is the coefficient is taken to be 0.03 at the central drive of the mechanism and 0.01 – with the separate drive; a is the minimum approach of the crane hook to the axis of the crane rail.

In the course of the probabilistic calculation of the effect on the frame of the building of the ship's hull workshop of the Astrakhan Marine Plant of horizontal forces caused by the operation of bridge cranes, the values of the numerical characteristics of bending moments are determined. A graphical interpretation of the results of the study on the individual components of the crane load in the most loaded transverse frame is presented in the form of corresponding diagrams. In figure 4, the solid line shows the values obtained in the probabilistic calculation of the lateral force arising from one crane, the dotted line in the normative calculation for the braking of crane trolleys of two cranes.

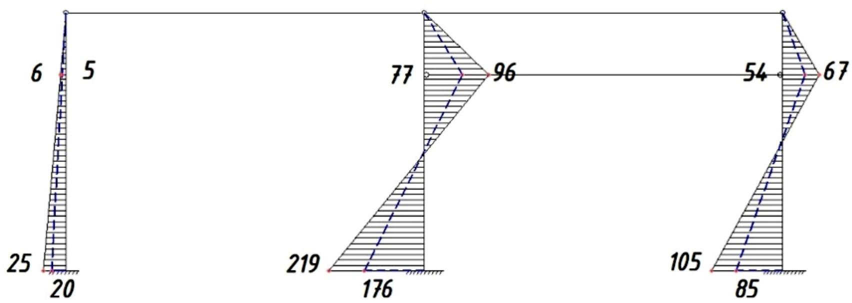


Figure 4. Diagram of bending moments from lateral force and braking of the crane truck (kN m).

Analyzing the obtained data on horizontal crane loads, we can see that the values of bending moments under the action of the lateral force of one crane, determined in the probabilistic setting, are 25 % higher compared to the values of bending moments obtained in the normative calculation from the braking of crane trucks of two cranes at once. The demonstration of the calculation results proves the need to take into account when forming combinations of the simultaneous action of the loads of all the considered components of the crane load. Each of them makes a significant contribution to the total load.

Thus, as a result of experimental and theoretical studies, refinements have been made to the previously proposed design schemes and methods for calculating industrial loads on crane loads, allowing to design the supporting structures of frames in accordance with the actual conditions of their actual operation.

In probabilistic modeling, snow load values are taken as the initial distribution of a continuous random variable of a sequence of annual maximums $\left(S_{m\,i}\right)$ by Gumbel distribution law (7)-(8). Its parameters α and β are calculated through mathematical expectation m_{S_m} and the standard σ_{S_m} of a sample of data from meteorological observations:

$$\alpha = m_{S_m} - k_\alpha \sigma_{S_m} \quad \beta = k_\beta \sigma_{S_m} \tag{18}$$

Considering the known volume of the specified aggregate $\left(S_{m\,i}\right)$ as N, Gumbel table coefficients k_α and k_β are approximated as:

$$k_\alpha = 0.45 + 0.34N^{-0.69} \quad k_\beta = 0.78 + 1.54N^{-0.75} \tag{19}$$

Therefore, their limit values are equal to: $k_\alpha = 0.45$ and $k_\beta = 0.78$.

For the possibility of carrying out probabilistic calculations for the perception of the snow load structure by the frame of an industrial building, we express the numerical characteristics of the random value of its annual maximums through the Gumbel distribution parameters α and β.

Taking as the value of the maximum weight of snow cover exceeded on average once $T_0 = 25$ years, the provision of snow load will be:

$$F\left(S_g\right) = 1 - \frac{1}{T_0} = 0.96\,. \tag{20}$$

Expressing from (8) the magnitude of the load, we obtain:

$$S_g = \alpha - \beta \ln\left(-\ln\left[F\left(S_g\right)\right]\right) \tag{21}$$

Thus, between groups of indicators $\left(S_g, m_{S_g}, \sigma_{S_g}\right)$ and $\left(\alpha, \beta\right)$ there are ratios:

$$\begin{cases} S_g = \alpha - \beta \ln\left(-\ln\left[1 - \dfrac{1}{T_0}\right]\right) \\ m_{S_g} = \alpha + \dfrac{k_\alpha}{k_\beta}\beta \\ \sigma_{S_g} = \dfrac{1}{k_\beta}\beta \end{cases}. \tag{22}$$

Considering the value of the reliability index β_{S_g} in the following form:

$$\beta_{S_g} = \frac{S_g - m_{S_g}}{\sigma_{S_g}}, \tag{23}$$

considering the derived dependences (22) and the limit values of the Gumbel coefficients k_α and k_β we have:

$$\beta_{S_g} = k_\alpha - k_\beta \ln\left(-\ln\left[1 - \frac{1}{T_0}\right]\right) = 0.45 - 0.78 \cdot \ln\left(-\ln 0.96\right) = 2.045 \tag{24}$$

When substituting a numerical value β_{S_g} in (23) a probabilistic model of snow cover weight, evenly distributed over a horizontal surface, is displayed as:

$$S_g = m_{S_g} + \beta_{S_g}\sigma_{S_g} = m_{S_g}\left(1+\beta_{S_g}\frac{\sigma_{S_g}}{m_{S_g}}\right) \quad \Rightarrow \; S_g = m_{S_g}\left(1+2.045\cdot Var\left(S_g\right)\right) \tag{25}$$

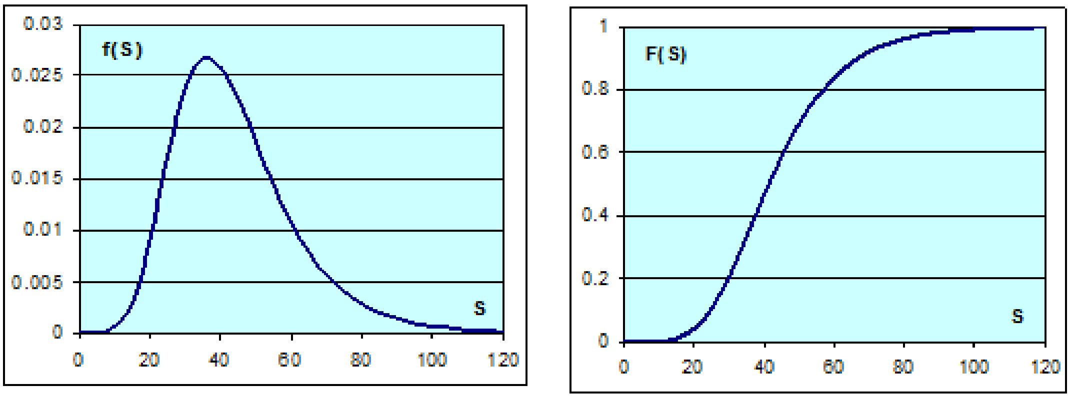
where $Var\left(S_g\right)$ is the coefficient of variation of annual maximums of snow cover weight for a specific area.

Taking the average value of the coefficient of variation for most of the snow regions of the Russian Federation equal to 0.4, a numerical implementation of the presented model is obtained (Table 1).

Table 1. Indicators of the distribution of snow load.

No of snow district	Numerical characteristics		Gumbel distribution parameters	
	m_{S_g}	σ_{S_g}	α	β
I	44	17.6	36.08	13.73
II	66	26.4	54.12	20.59
III	99	39.6	81.18	30.88
IV	132	52.8	108.24	41.18
V	176	70.4	144.32	54.91
VI	220	88.0	180.40	68.64
VII	264	105.6	216.48	82.37
VIII	308	123.2	252.56	96.11

Most of the industrial buildings, the work of which framework for the action of various combinations of loads was studied in the course of research by the authors of the article, are located on the in the territory belonging to the I snow region. A graphical representation of the distribution law of the random value of annual maxima for the calculated values of the parameters (Table 1) for a given area has the following form (Fig. 5):



a) Distribution density **b) Distribution function**

Figure 5. The random distribution of annual maxima of snow cover weight S_g $\left(kgs/m^2\right)$ for the territory belonging to the I snow region.

The magnitude of the total snow load on the floor of a building or structure, in addition to the weight of snow cover on a horizontal surface of the earth, is influenced by a large number of other factors. They are considered in the total snow load on the coating of an industrial building by introducing coefficients μ, c_e and c_t into the design model:

$$S_{snow} = \mu\, c_e\, c_t\, S = \mu\, c_e\, c_t \left[\gamma_f\; 0.7 m_{S_g}\left(1+2.045\cdot Var\left(S_g\right)\right)\right], \tag{26}$$

where μ is the coefficient taking values on the choice of the form of coverage, c_e is the coefficient taking into account the drift of snow from the surface under the action of wind and other factors, c_t is the thermal coefficient taking into account snow thawing on non-insulated coatings of workshops with increased heat generation at roof slopes of over 3 % for removal of meltwater.

The snow load model obtained in the course of the study is in good agreement with the probabilistic approach to determining the components of the load factor based on mathematical expectations and indicators of variation of their values. It is adapted for software implementation by means of a computer through the "DINCIB-new" computational complex developed by the authors of the article.

The appearance of wind, as a natural phenomenon, is explained by the movement of air masses from high zones to lower pressure zones. The level of friction between the air flow and the surface depends on the height and density of the obstacles, which determines the magnitude and direction of the corresponding load on a particular object. Moving away from the surface of the earth, the wind speed gradually increases until a gradient level is reached, i.e. to the level at which the friction force ceases to influence the movement of air masses.

The mathematical expectations of a random wind pressure field when determining the regularities of the territorial variability of the calculated parameter are presented in the form of standard values w_0 at a height of 10 m above the ground. For example, in accordance with the standards adopted in the Russian Federation, their values can be presented in Table 2.

Table 2. The standard value of wind pressure in the regions of the Russian Federation.

Wind areas	Ia	I	II	III	IV	V	VI	VII
w_0, kPa	0.17	0.23	0.30	0.38	0.48	0.60	0.73	0.85

On the territory of each selected zone of the Russian Federation, there are areas of different type of belonging, and, consequently, different gradient levels.

To obtain calculated values and automated processing of the wind load on the blown surface area of an industrial building located at a height z, in the course of this study, the profiles of wind flow velocity at various heights were approximated (Table 3). A functional dependence has been obtained, which has a clearly expressed power-law character, since the determination coefficient R^2 is close to 1.

Table 3. Wind flow velocity at height z depending on the type of terrain.

Type A	*Type B*	*Type C*
$z_0 = 10$ m	$z_0 = 30$ m	$z_0 = 60$ m
$k = \left(\frac{z}{z_0}\right)^{0.31}$, $R^2 = 0.9883$	$k = \left(\frac{z}{z_0}\right)^{0.39}$, $R^2 = 0.9976$	$k = \left(\frac{z}{z_0}\right)^{0.46}$, $R^2 = 0.9855$

The regression dependences of the wind pressure on the height of the stretched area of the industrial building (Table 3) obtained during the study provide a convenient form for automating the calculations.

The proportion of the velocity head of the wind, turning into pressure on the surface of the building, is expressed as the aerodynamic coefficient. Its value C is determined by:

- the direction of the undisturbed flow;
- the nature of the flow around the geometric forms of the building by the air flow;
- location of the zones of vortex formation and turbulence;
- the presence near the object of study of other obstacles, both natural and man-made.

The distribution of aerodynamic coefficients varies significantly with a small change in the force and direction of the wind flow. This fact orients further research of aerodynamic characteristics on the use of computer-aided design and simulation, implemented by a computer.

To describe the dynamic parameters of the process, presented in the form of the pulsation component of the wind load and the reactions of the structural elements of the building caused by it, the study examined random functions by the time parameter. They display the energy spectrum $S(\omega)$ of the fraction of the power of the wind flow falling on an infinitely small frequency range $d\omega$. The standards adopted in the Russian Federation are based on the use of the spectrum proposed by A. Davenport:

$$S(\omega)=\frac{8\pi u^2}{3\omega\left(1+u^2\right)^{\frac{4}{3}}},\qquad(27)$$

where ω is the circular frequency of exposure, $u=\frac{\omega L}{2\pi\upsilon_0}$ is the dimensionless design frequency, $L=1200$ m is turbulence scale, υ_0 is the average wind speed at a height of 10 m.

This representation of the spectral density considers only the change in the velocity of the wind flow in the time parameter. If we also take into account the spatial dependence, then the mutual spectrum of pulsations at two specific points in the space i and j can be analytically described [29], as:

$$S_{ij}(\omega,\chi)=\frac{2\pi u^2}{3\omega\left(1+u^2\right)^{\frac{4}{3}}}e^{-u\chi_{ij}},\qquad(28)$$

where χ_{ij} is the reduced distance between points i and j.

The aggregate of mutual spectral densities $S_{ij}(\omega,\chi)$ when choosing points of space, each of which determines the closeness of the relationship between the states of a random process $\upsilon_i'(t)$ and $\upsilon_j'(t)$ in the frequency range $[\omega,\ \omega+d\omega]$, allows you to set the value of the correlation coefficient of the pulsations of the wind pressure ν for the entire surface of the building, perceiving the appropriate load.

An industrial building is a technical system with a large, but finite, number of degrees of freedom. For such a system, the dynamic calculation of the pulsation component of the wind load for all s-forms of natural oscillations, the frequencies of which do not exceed the limiting value f_l, i.e. the condition is met:

$$f_s<f_l<f_{s+1}\,.\qquad(29)$$

All the buildings of the shops, the change in the stress-strain state during the operation of which was studied in the course of this study, are located in the territory of the Astrakhan region, correlated to the third wind region. Since they all belong to the class of objects with a steel frame in the presence of enclosing structures, the logarithmic decrement of oscillations is assumed to be $\delta=0.3$, and the corresponding frequency limit is $f_l=1.2\ Hz$. The study found that for each of these industrial buildings $s>1$.

So, for example, for the building of the ship hull workshop of the Astrakhan marine shipbuilding plant, the distribution of the first 10 circular frequencies of natural vibrations is shown in Table 4.

Table 4. Own circular oscillation frequency of the building of the ship hull workshop.

i – form number	1	2	3	4	5	6	7	8	9	10
$\omega_i,\left(\sec^{-1}\right)$	4.13	4.39	24.57	25.4	25.55	25.67	25.71	25.92	26.11	27.78

Consequently, $s=2$, insofar as:

$$\omega_l=2\pi\cdot f_l=7{,}536\ \sec^{-1}\quad\Rightarrow\quad\omega_1<\omega_l\quad u\quad\omega_2<\omega_l\,.\qquad(30)$$

For the adopted design schemes of single-storey industrial buildings equipped with bridge cranes, when wind load is included in the complex loading, its pulsation component at the level of z, corresponding to i-form of natural oscillations, was determined by the formula:

$$w_p^i=M\xi_i\psi_iY_i\qquad(31)$$

where M are mass of the building to which the load is applied; ξ_i is the dynamic factor for *i* form period; ψ_i is the main indicator that determines the magnitude of the load; Y_i is the horizontal movement of the frame with *i*-waveform.

The magnitude of the coefficient of dynamism at known values of the logarithmic decrement of vibrations $\delta = 0.3$ and wind load reliability indicator $\gamma_f = 1.4$ becomes dependent on the parameter

$$\varepsilon_i = \frac{\sqrt{\gamma_f \ k \ w_0}}{940 f_i} = \frac{\sqrt{\gamma_f \ k \ w_0}}{150 \ \omega_i} \qquad (32)$$

graphical interpretation (Fig. 6) of which for the possibility of software processing by computer with varying ε_i in the range of [0; 0.2] approximate as:

$$\xi_i = -22.82\varepsilon_i^2 + 10.32\varepsilon_i + 1.03 \qquad (33)$$

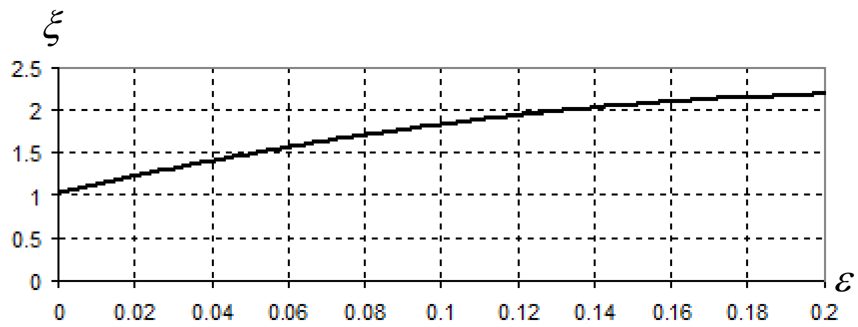


Figure 6. The coefficient of dynamic.

A dependency graph $\xi = \xi(\varepsilon, \delta)$ is correlated on the assumption of the uniformity of the distribution of pulsations of wind speed over the entire surface, perceiving the load.

Value ψ_i depends on the parameters r plots sW8plitting the industrial building, within each of which the wind load value is taken constantly. These include the resultant ripple of the specified load on the k-segment, which is determined by the product

$$w_{pk} = w_{mk} \ \zeta_k \ v_k \qquad (34)$$

average static wind load w_{mk} (10), wind pressure ripple factor ζ_k and its spatial correlation of mutual spectral densities v_k (28) on this area.

Considering in the calculations the mass of each section m_k and horizontal movement of its center y_k, the dependence between the parameters when searching for an indicator ψ_i is taken as:

$$\psi_i = \frac{\sum_{k=1}^{r} y_{ki} \ w_{pk}}{\sum_{k=1}^{r} y_{ki}^2 \ m_k}. \qquad (35)$$

When studying the effects of wind load on the work of the frame of an industrial building, the corresponding reactions of the system elements were determined separately from the average $X^s = X(w_M)$ and the sum of the pulsating components $X^d = X\left(\sum_{i=1}^{s} w_p^i\right)$. The cumulative effect corresponding to the most unfavorable load value is achieved in case of coincidence of their signs:

$$X = X^s + sign\left(X^s\right)\cdot X^d . \quad (36)$$

The considered approach to the assessment of forces caused by the action of the wind, and reactions to them by the research object, is the basis of the calculation methodology, as one of the components of the generalized load, causing movements of the nodes of the design scheme, and, as a result, the change in stresses in the structural elements.

The implementation of the research concept is based on the probabilistic approach as the most appropriate for the random character of technogenic [9, 10] and extreme impacts [26, 29]. Generating the values of random variables applied crane loads, subject to the normal distribution law with known parameters of the expectation and standard deviation, each of the corresponding embedded calculation algorithms is repeated a large number of times, which allows achieving high accuracy of the results. To be able to compare them with the standard values under equal conditions, the algorithm also implies an appropriate calculation without considering the random nature of the manifestation of disturbing influences.

4. Conclusions

As conclusions on the results of the study, we highlight the following:

1. Clarifications have been made to the previously proposed design schemes and the methodology for calculating industrial buildings for crane and atmospheric loads, allowing to design the supporting structures of the frames in accordance with the actual conditions of their actual operation;

2. The necessity of calculating bending moments for all variants of the time variation of the total braking force of the trolleys of two adjacent cranes and the choice of the largest of them for loading design is substantiated;

3. The assumption is confirmed that the oscillations caused by the lateral forces during the tilted movement of the crane, directed across the rail tracks, have significantly larger amplitudes than when braking the crane truck;

4. Demonstrated good consistency of the proposed models of snow and wind loads, adapted for software implementation by means of computers, with a probabilistic approach to determining the components of the load factor.

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Contacts:

Tatiana Zolina, zolinatv@yandex.ru
Pavel Sadchikov, pn_sadchikov@mail.ru